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Investigation of Current Distribution in Multi-Tape HTS Samples.

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Abstract

One of the main problems in multi-element superconductors is to ensure the current distribution between several elements in accordance with their individual critical currents.

The experimental investigation of self-field current redistribution between several HTS tapes was performed in order to support the design of a resistive type SFCL. The critical currents at 1 μV/cm of 12 mm wide tapes SF12100 produced by Super Power were in the range 210-300A at 78 K temperature. The rated rms current of SFCL project is 900 A.

The samples were wound onto about 200 mm diameter bobbin and consisted of one or two layers of 3 or 6 connected in parallel HTS tapes. The multi-tape conductor turns were at first charged with DC or AC (50Hz) individually. Then they were mounted coaxially and connected in opposite in order to reduce self-field and inductance values. The dynamic behavior of currents in the tapes was reconstructed from simultaneously measured data of 7 Hall probes and V-A curves of several tapes.

In spite the critical currents of individual tapes were far from being equal the total critical current of the samples was close to the sum of tapes critical currents (about 750 A for 3 tapes and 1350 A for 6 tapes). Some recommendations for the improvement of current distribution uniformity are given for the case of SFCL.

Keywords: superconducting fault current limiter, coated conductor

Introduction

The actual problem for distribution level electrical grids, especially for railways, is the protection from short circuit events, producing fast wear and damage of the electrical equipment. The statistical investigations show, that short circuit events are several times more frequent in railway, compared to usual distribution grids. Recovery time after shorting in railway can be long enough (several seconds) against 1 s in usual distribution grids. The most effective protection, considering limiting time and losses during long-term operation is superconducting fault current limiter (SFCL), both to AC and DC applications. There are many different SFCL types, for example, described [1], [2]. We have chosen the

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resistive type SFCL bifilar coils design. Technical requirements for 3.5 kV, 250 A rms and 27.5 kV, 900 A SFCL devices for company “Russian Railways” were worked out.

The coated conductor Super Power SF12100, without stabilizing copper, was used. The Ag layer thickness is only 1 μm, therefore the resistance of this tape in normal state is high enough to be used in resistive type SFCL. But the resulted the local normal zone does not propagate because of low thermal conductivity and a tape burns out in relatively short time.

The normal zone propagation process was studied for this tape. DC charged sample was normalized by a small external electromagnet and the voltages of the central and neighboring part were measuring, and reconstructed in the corresponding temperatures. It was found that normal zone almost did not propagate until the normal part burned out in 0.3 s. Therefore a protective circuit should be used with sensitivity high enough to detect short normal zone.

To provide the SFCL safe operation, we also protected HTSC tapes by high resistive 20 μm tape from NbTi foil coated with 1 μm copper layer. The protective tape on the superconducting sides of the tapes reduces temperature of normal zones because of high thermal and electrical conductivity of copper.

Current of the whole tape was from 210 to 300 A on level of electrical field 1 μV/cm. The value is too low for most of SFCL applications, therefore tapes should be connected in parallel, 2 tapes for 250 A rms, and 6 for 900 A rms. We use two layers of 3 tapes to minimize the device dimensions.

The 380 V 250 A rms limiting element wound by 2 HTSC tapes and protective tape, and also 3.5 kV SFCL made from 8 elements, were built and successfully tested at long-term operation and different short circuit events types [3].

HTS AC losses and copper joints heat emission were reconstructed from the VAC measurements. HTS AC losses are small in comparison with the heat emission of copper joints, current leads and cryostat for long term operation current. AC losses do not determine the cooler power for the case of SFCL. Therefore there is no necessity to use Roebel current element or any other conductor with low losses. From the point of view of stability the use of parallel tapes at AC operation is correct because n parameter of HTS is low in comparison with LTS one.

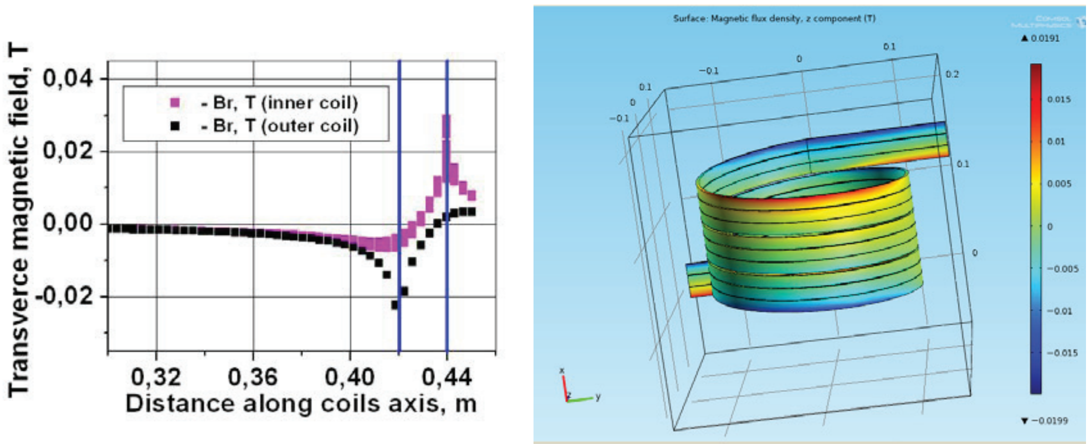

Fig.1. a) Radial (transverse to tapes) field near the windings of inner coils pair of 27,5 kV SFCL. Transverse field peaks are visible at the edges of both windings, at x = 0,42 m and 0,44 m.
b) Field distribution for the 3-turn model sample section calculated by finite elements method. Transverse field peaks (about ± 0,02 T) are visible at the edges of the edge tapes of the edge turns (red and deep blue).

The 6 tape current element design for 900 A rms 27,5 kV SFCL, consisting of 10 pairs of coils connected in opposite has been developed. It was necessary to investigate current distribution and current capacity for DC and AC, field distribution influence, and take measures to increase edge turns current capacity.

The general problem of current elements consisting of several parallel HTSC tapes is providing current distribution between tapes in accordance with their current capacities. At DC this distribution is determined by soldered joints quality (identity) and tapes current capacities.

Current capacity field dependence of the tape at 77K is strong and significantly anisotropic. There is a peak of transverse magnetic field, see Fig. 1a), decreasing current capacity of edge tapes and because of it the whole device operating current, especially at AC. We propose to shunt the edge tapes at edge turns by additional HTSC tapes to increase the total current capacity.

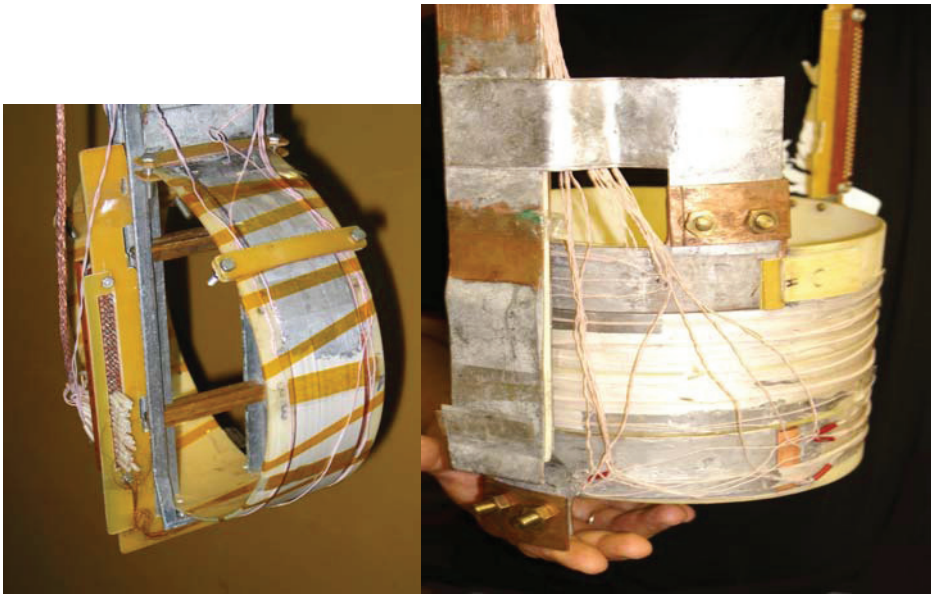

Fig. 2 a) 1-turn model sample with 6 tapes and protective tape b) 3-turn model sample with 3 tapes and 2 additional tapes at the edge turns.

Model samples investigations experimental details

Current distribution and current capacity at several model samples, see Fig.2 and Fig.3 b) were investigated. Voltages at all tapes, some parts of the tapes, soldered joints with copper current leads were simultaneously measured. Individual tapes currents have been reconstructed from Hall probes data, in accordance with field calculation presented at Fig. 3a). The influence of neighboring tapes currents to the Hall probe, situated near a tape center is insignificant. Sum of currents, reconstructed from Hall probes, coincide with total current with uncertainty 5-10% (the calculation does not consider current distribution inside the tape, shielding currents). Transverse field at the edges of edge turns was also measured at some tests.

Results

DC capacity of the 1-turn model sample with 6 HTSC tapes is about 1250A at 10 μV/cm and 1350 A at 100 μV/cm. The sample 900 A rms operation is stable, at about 1000 A rms the sample warms up to normal state.

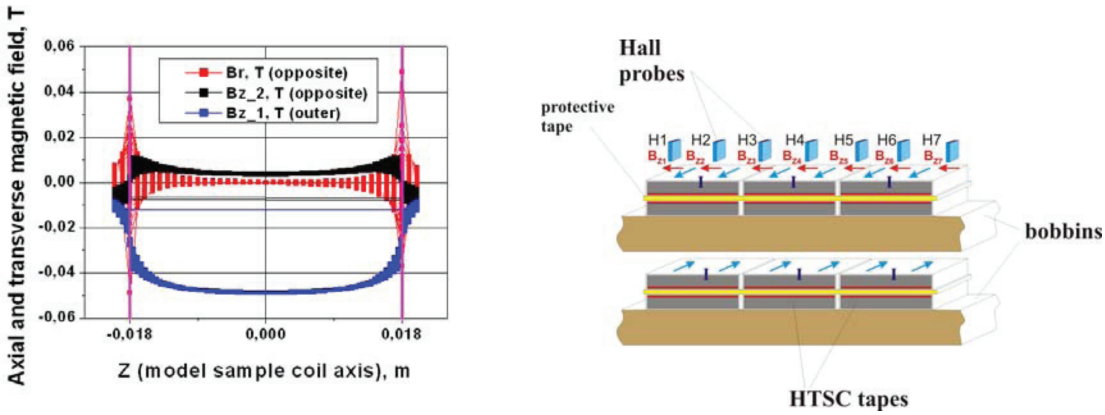

Fig.3. a) Field distribution calculation at 250 A current of each tape for reconstruction tapes currents from Hall probes data. b) Model sample and Hall probes positions.

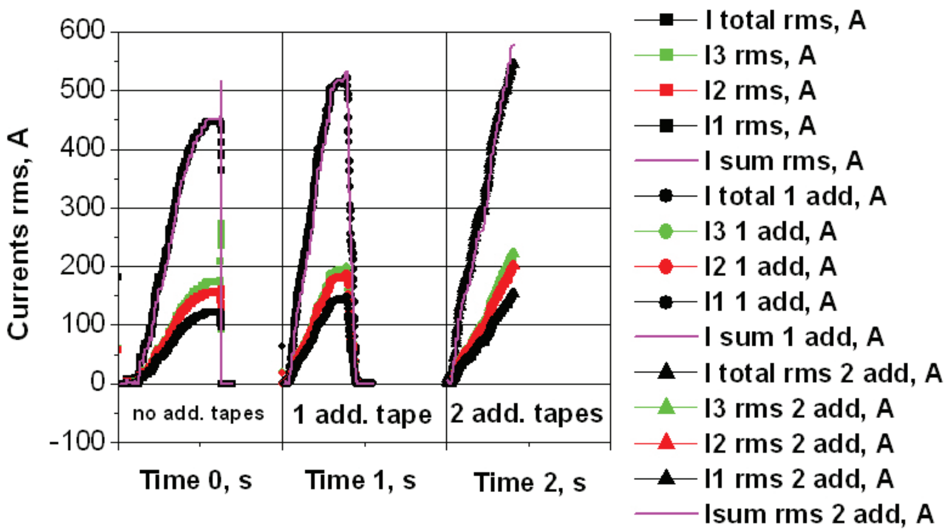

Fig.4. Total current rms and tapes currents rms versus time at 3 turn model sample with 3 tapes without additional tapes, with additional tape at tape N1, with 2 additional tapes at tapes N1 and N3.

DC capacity of the 3-turn model sample with 3 HTSC tapes is about 750A at 10 μV/cm. Initial AC capacity was 450A rms. Shunting the edges by the additional tapes increased the whole model sample current capacity to 550 A rms, see Fig.4.

Soldered joints VACs influence to current distribution is presented at Fig.4a),b). Superconducting parts of joints VACs can regulate the currents distribution between tapes.

3 turn model sample with 3 tapes, with DC distribution 250 A DC at the middle tape, 50 and 75 A (tapes were damaged) at the edges has been investigated, see Fig.6b). The sample currents were distributed between tapes almost homogenously at AC, therefore at AC opposite connected coils self field reduces and current capacity increases. Measured field at the edge of edge tape of external section edge turn is 0,01 T at currents of each tape about 100 A, and in case of opposite connection of two sections field is 0,005 T at currents about 140 A. Transverse field distribution at 2 parallel oppositely connected 3-tape conductors calculated by finite element method is presented at Fig.6a), peaks at the edges are visible.

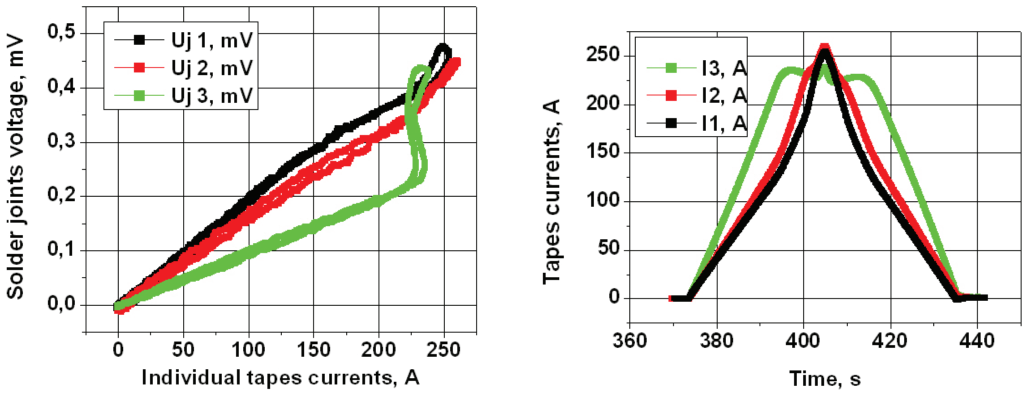

Fig. 5 a) Joints voltages versus tapes currents b) tapes current distribution versus time

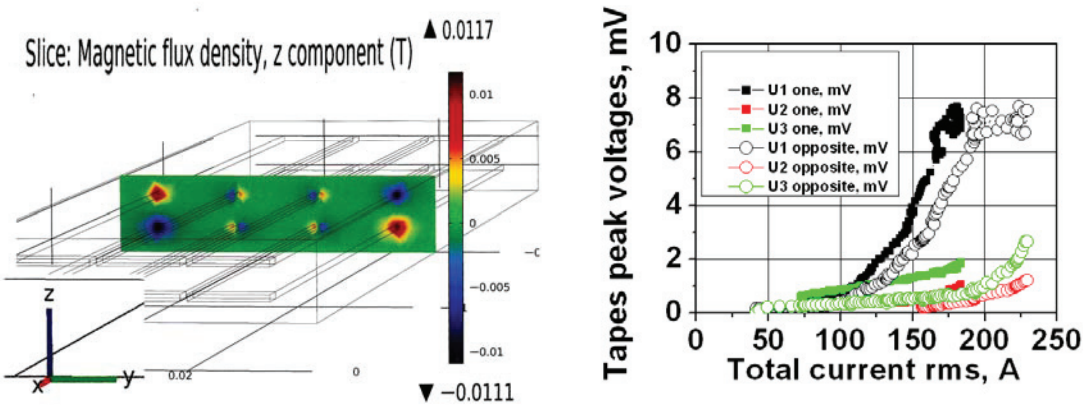

Fig.6 a) Transverse field distribution for 2 parallel 3-tape conductors with opposite currents of each tape 250 A.
b) AC peak tapes voltages versus tapes rms currents for 3-turn model sample outer section and for this section in case of two model sample sections connected in opposite.

Conclusions

-Currents are distributed between tapes in accordance to their different individual current capacities. The total current capacity of the samples of several parallel tapes is close to the sum of all tapes current capacities.

-DC distribution between parallel HTSC tapes is conditioned by soldered joints resistance and tapes VACs, AC distribution is done by tapes inductance and AC distribution with high VAC level is done by inductance and tapes VACs.
-Additional HTSC tapes at the edges of the edge turns increase the total SFCL operating current.
-Tapes with more homogenous current capacities should be applied for AC than for DC.
-Protective circuit breaking should be applied and should to detect the short normal zones.
-Current capacity of coils connected in opposite increases in case of homogenous current distribution.

Acknowledgment

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